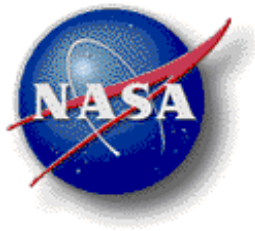# STRUCTURAL VERIFICATION PLAN

for

Human Research Facility (HRF) Muscle Atrophy Research and Exercise System (MARES) Rack and Payload Equipment

Space and Life Sciences Directorate

Flight Projects Division

July 2003

**National Aeronautics and
Space Administration**

**Lyndon B. Johnson Space Center
Houston, Texas 77058**

LMSEAT 34144

STRUCTURAL VERIFICATION PLAN

for

Human Research Facility (HRF) Muscle Atrophy Research and Exercise System (MARES) Rack and Payload Equipment

BSD Task Order 1 (WBS2.7.1)

Contract NAS 9-02078

Review Draft

Prepared by

Lockheed Martin Space Operations
Houston, Texas

Prepared for

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Space and Life Sciences Directorate

National Aeronautics and Space Administration
Lyndon B. Johnson Space Center
Houston, Texas

May 2003

STRUCTURAL VERIFICATION PLAN

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Human Research Facility (HRF) Muscle Atrophy Research and Exercise System (MARES) Rack and Payload Equipment

NASA Approval

_____
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National Aeronautics and Space Administration
Lyndon B. Johnson Space Center
Houston, Texas

May 2003

STRUCTURAL VERIFICATION PLAN

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Human Research Facility (HRF) Muscle Atrophy Research and Exercise System (MARES) Rack and Payload Equipment

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May 2003

LMSEAT 34144

STRUCTURAL VERIFICATION PLAN

for

Human Research Facility (HRF) Muscle Atrophy Research and Exercise System (MARES) and Payload Equipment

Revision History

Revision	Date	Rev By	Pages Affected	Remarks
Baseline				

0.2   LIST OF FIGURES

Figure   **Page**

0.3   LIST OF TABLES

Table   Page

0.4   ACRONYMS AND ABBREVIATIONS

Generally, symbols are defined where they appear within the body of the text.

APM	Attached Pressurize Module
AVT	Acceptance Vibration Test
ESA	European Space Agency
FEM	Finite Element Model
FLAGRO	??
FS	Factor of Safety
g	gravity
grms	gravity, root mean square
GSE	Ground Support Equipment
HRF	Human Research Facility
Hz	Hertz
ISPR	International Standard Payload Rack
ISS	International Space Station
JSC	Johnson Space Center
Kg	Kilogram
LMSO	Lockheed Martin Space Operations
LSA	Launch Structure Assembly
LSP	Launch/Stowage Plate
lb	Pound
MARES	Muscle Atrophy Research and Exercise System
min	minute
MPLM	Mini Pressurized Logistics Module
MSFC	Marshall Space Flight Center
NASA	National Aeronautics and Space Administration
NASTRAN	NASA Structural Analysis Program
NSTS	National Space Transportation System
PFE	Portable Fire Extinguisher
psi	Pounds per Square Inch
rad	radians
s	seconds
QVT	Qualification Vibration Test
Ref.	Reference
ROM	Range of Motion
RSP	Re-supply Stowage Platform
STS	Space Transportation System
SUP	Standard Utility Panel
TBD	To Be Determined
TVFEM	Test-Verified Finite Element Model
UF-3	Utilization Flight 3

UIP   Utility Interface Pane
UOP   Utility Outlet Panel
VIF   Vibration Isolation Frame

1. PURPOSE

The purpose of this plan is to present the analysis scope and approach for conducting structural analysis and verification for the Human Research Facility (HRF) Muscle Atrophy Research and Exercise System (MARES) Rack and its payload complement. The MARES Rack is currently scheduled to launch on the International Space Station Utilization Flight 3 (UF-3) Mission. The details presented in this plan are in accordance to the International Space Station Program and Space Shuttle Program strength and frequency requirements, as defined in ISSP Pressurized Payloads Interface Requirements Document, SSP 57000E, and ISSP Payload Flight Equipment Requirements and Guidelines for Safety-Critical Structures, SSP 52005B, and other applicable documents.

In addition to analysis scope and approach, this plan contains description of math model requirements, load factors for design and analysis, design factors of safety, thermal and pressure considerations, verification approach, and a list of deliverables applicable to the MARES Rack and payload.

2. OVERVIEW

The HRF MARES Rack is a facility-class payload that accommodates the launch, deployment, and stowage of the HRF Muscle Atrophy Research and Exercise Systems (MARES). The MARES Rack also serves as a mechanical interface to a Power Interface Panel (PIP) that routes electrical power for the MARES from the Utility Interface Panel (UIP) or Standard Utility Panel (SUP)/Utility Outlet Panel (UOP). The MARES Rack is to be launched in the MPLM on Flight UF-3 and installed in a rack space within the ESA Columbus Module after launch. Following deployment on orbit, the MARES will be used for research on musculoskeletal, biomedical, neuromuscular, and neurological physiology and to evaluate the effect of the countermeasures to the space induced physiological effects on human beings.

3. DESCRIPTION OF STRUCTURES

The main components of the MARES Rack include a four-post International Standard Payload Rack (ISPR) that serves as a launch, stowage, and deployment platform for the MARES; the MARES integration structures; the MARES; the MARES Rack stowage drawer; and the soft-stowage bags.

3.1 ISPR STRUCTURE

The ISPR structure used for the MARES Rack will be a modified 4-post ISPR. Modifications to the ISPR include replacement of the upper intercostal with a recessed version to allow additional stowage space and installation of rack post stabilizers for local structural enhancement to the rack posts.

3.2 MARES INTEGRATION STRUCTURES

The MARES integration hardware includes the Launch Structure Assembly (LSA), the Launch/Stowage Plate (LSP), the Right and Left LSP Support Structures, the soft-stowage bags, the stowage drawer, and the seat track adaptors. The LSA, LSP, and the Right and Left LSP Support Structures serve as interface support between the ISPR and the MARES for the launch configuration. The LSA is eliminated and only the LSP and Right and Left LSP Support Structures are used for the on-orbit stowed configuration. For the on-orbit deployed configuration, the seat track adaptors serve as the interface support between the ISPR and Vibration Isolation Frame (VIF). The soft-stowage bags and stowage drawer will provide housing of MARES peripheral equipment for lift-off, landing, and on-orbit stowage.

The MARES integration hardware also includes the PIP that is an electrical interface for the MARES experiment from the UIP or SUP/UOP. The PIP is soft stowed for launch and mounted to the seat track when supporting MARES operations.

3.3 MARES

The main structural components of the MARES include the Main Box Assembly, the Chair, the Pantograph, and the Vibration Isolation Frame (VIF).

3.3.1 *Main Box Assembly*

The MARES Main Box contains a motor, micro-controller, electronic subsystems that includes a Ni-Cad battery weighing approximately 27 lbs, heat rejection systems and angular motion and

torque sensors. The MARES Main Box also includes fans to circulate the ISS module cabin air (in open loop) and cool down the different MARES subsystems.

3.3.2   *Chair*

The MARES Chair is an articulated support device that stabilizes the subject during the exercises and minimizes the influence of other muscle contractions on the measurement.

3.3.3   *Pantograph*

The Chair is connected to the Main Box through the Pantograph. The Pantograph allows positioning of the subject's joint under study aligned with the motor shaft so that the load path of the subject's exercise will stay internal to MARES for the entire range of the eligible population.

3.3.4   *Vibration Isolation Frame (VIF)*

The VIF is a spring-damper frame that serves to abate the perturbation of the microgravity environment of ISS while MARES is in use. At the same time, the VIF keeps MARES in the correct position and limits the range of displacement of the equipment.

3.4   CONFIGURATIONS

For launch and landing, the MARES Main Box is fastened to the LSP via the LSA and the remaining equipment is soft-stowed in bags affixed to the LSP.

For the on-orbit stowed configuration, the MARES Main Box is fastened directly to the LSP. The hardware accessories will be placed in stowage bags in the free space in the cavity of the rack, around the Main Box, pantograph, chair, and VIF. All MARES accessories will be deployed only when needed for operations.

During on-obit operations, the MARES Main Box is attached to the Vibration Isolation Frame (VIF) by 4 locking mechanisms located at the back of the MARES main box. The VIF is secured to the rack seat tracks by a set of four Seat Track Adapters.

Figures 3-1 to 3-6 provide graphic details on launch and on-orbit configurations for the MARES Rack.

3.5   RESPONSIBLE ORGANIZATION

The MARES, including all peripheral hardware for the MARES experiment, and the VIF are to be designed, built, and verified by NTE/ESA according to the MARES Structural Verification Plan, MARES-0000-PL-177-NTE.

The ISPR is provided by OZ/ISS Payloads Office and modified by EB/Human Life Sciences Engineering Division. Structural analysis of the ISPR is to be performed by Boeing in accordance with SSP57007 [Ref. 3].

The MARES integration hardware are to be designed, analyzed, and fabricated by Lockheed Martin Space Operations. Details on the analysis methods for the integration structures are contained in this plan.
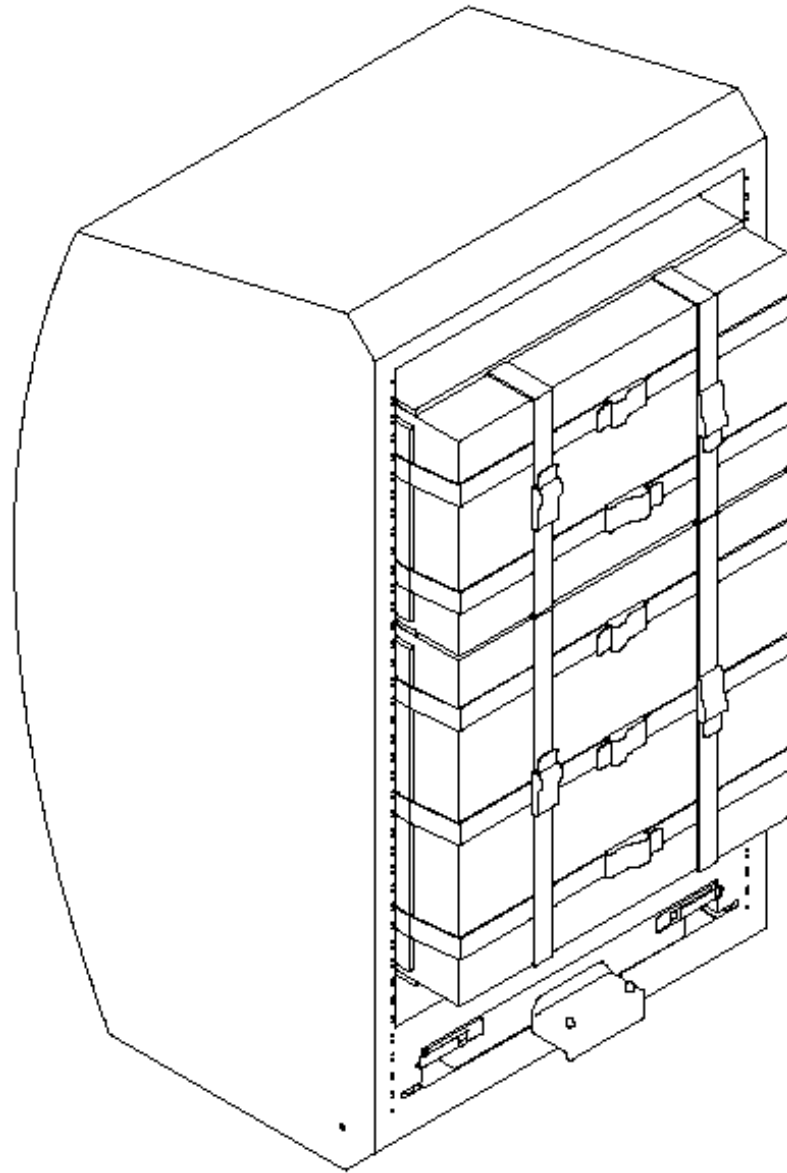
Figure 3-1: HRF MARES Rack, Launch Configuration

TPS SUPPORT STRUCTURE REMAINS MOUNTED TO RACK

MARES MAIN MOTOR BOX REMOVED FROM INTERFACE PLATE SHALL BE STOWED ON REPOSITIONED MARES LAUNCH/STORAGE PLATE

MARES LAUNCH/STORAGE PLATE TO BE REVERSED AND RE-MOUNTED TO SUPPORT STRUCTURE IN RACK

SEG33111506-501 MO2 BAG ASSEMBLY REMOVED FROM PLATE TO BE RETURNED

SEG33111505-501 MO1 BAG ASSEMBLY REMOVED FROM PLATE TO BE RETURNED

600461175D2-001 MARES INTERFACE PLATE REMOVED FROM MAIN MOTOR BOX AND RE-STOWED INTO THE MO1 BAG ASSEMBLY FOR RETURN

ALL STRAPS AND DIVIDERS SHALL BE REMOVED FROM MARES LAUNCH/STORAGE PLATE AND RE-STOWED INTO MO1 AND MO2 BAG ASSEMBLIES FOR RETURN

Figure 3-2: HRF MARES Rack, Launch Configuration (Exploded View)

MARES ON ORBIT ACCESSORIES
STOWAGE BAG

MARES VIBRATION ISOLATION
FRAME

MARES PANTOGRAPH
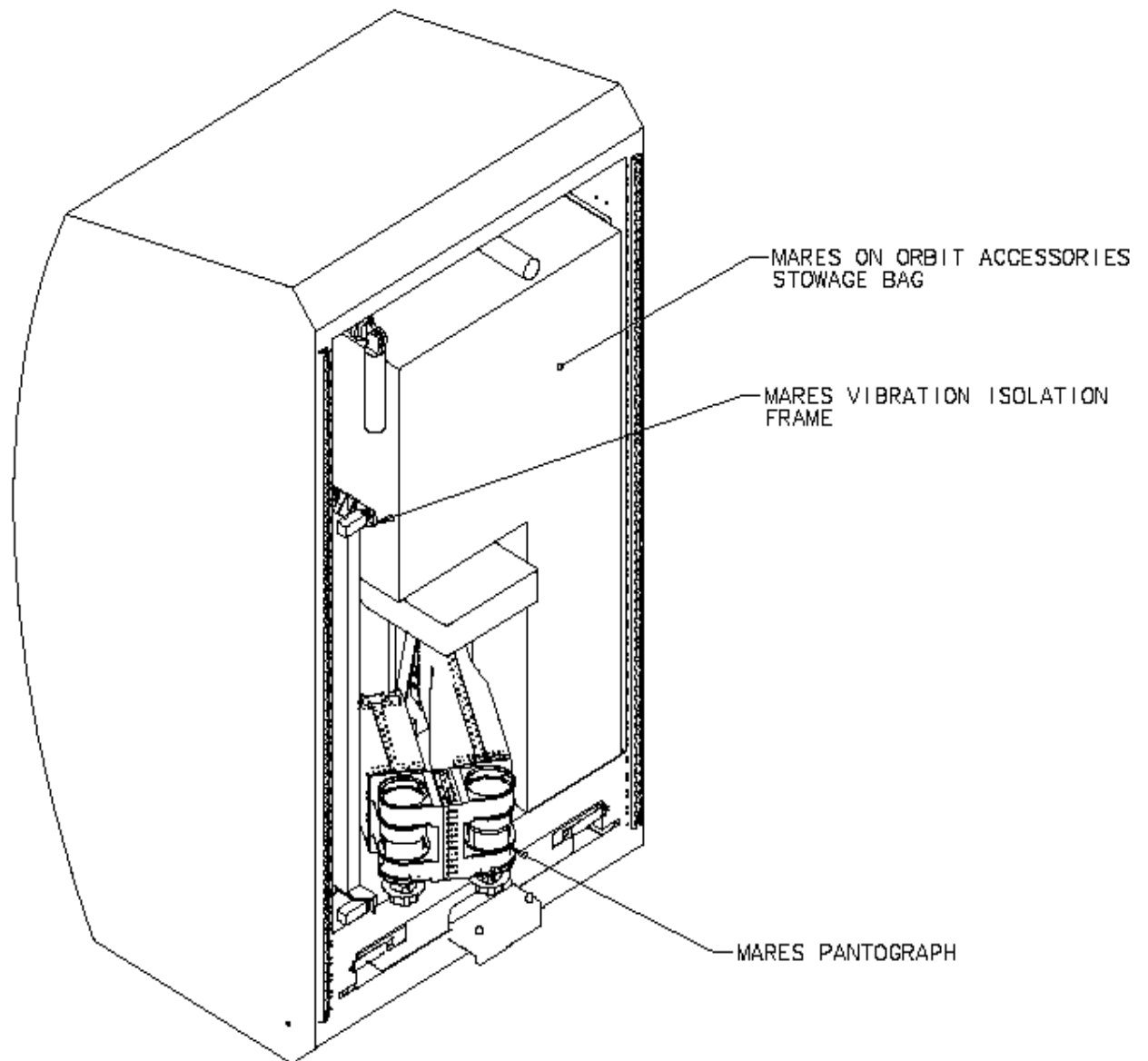
Figure 3-3: HRF MARES Rack On-orbit Stowage Configuration

RPS SUPPORT STRUCTURE

MARES LANCH/STOWAGE PLATE REVERSED SHALL BE RE-MOUNTED IN RACK ALONG BACK WALL AND ATTACHED TO SUPPORT STRUCTURE

VIBRATION ISOLATION FRAME LAUNCH BAG SHALL BE RE-USED FOR ON ORBIT STOWAGE OF MARES ACCESSORIES

ASSEMBLED MARES UNIT

MARES ON ORBIT ACCESSORIES STOWAGE BAG SHALL BE ATTACHED ON RPS SUPPORT STUCTURE IN RACK

RACK UTILITY STOWAGE DRAWER

MARES VIBRATION ISOLATION FRAME ASSEMBLED FROM LAUNCH BAG SHALL BE STOWED ATTACHED TO RPS SUPPORT STRUCTURE IN RACK

Figure 3-4: HRF MARES Rack, On-orbit Stowage Configuration (Exploded View)

MARES ON ORBIT ACCESSORIES STOWAGE BAG

MARES VIBRATION ISOLATION FRAME

RE-POSITIONED UPPER BODY RESTRAINTS

MARES SEAT BACK REST

MARES PANTOGRAPH

POWER INTERFACE PANEL (PIP)

MARES FOOT REST

MARES MAIN MOTOR BOX

Figure 3-5: HRF MARES Rack, On-orbit Deployment Configuration

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Figure 3-6: HRF MARES Rack, On-orbit Operation Configuration

4. DESIGN LOADS

Load requirements for the MARES rack and payload will be applied in accordance to Section 3.1.1.3 of SSP 57000E[Ref. 2]; Section 4.0 of SSP 52005B[]; and Section 3.2.1.4.2, Part 1, and Section 3.1.3, Part 2 of SSP41017B[Ref. 14].

The following sub-sections provide the load factors applicable to the MARES Rack and payload analysis.
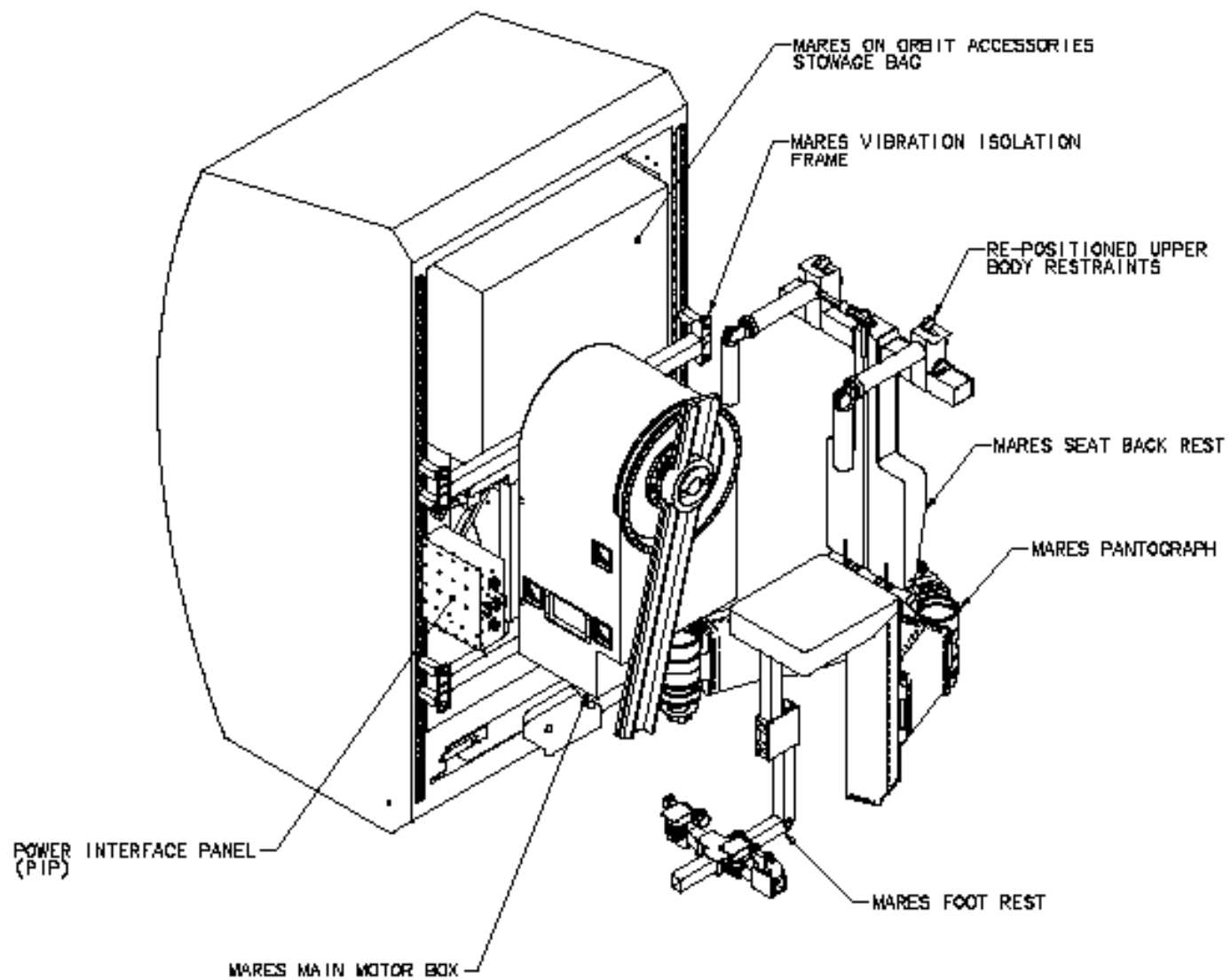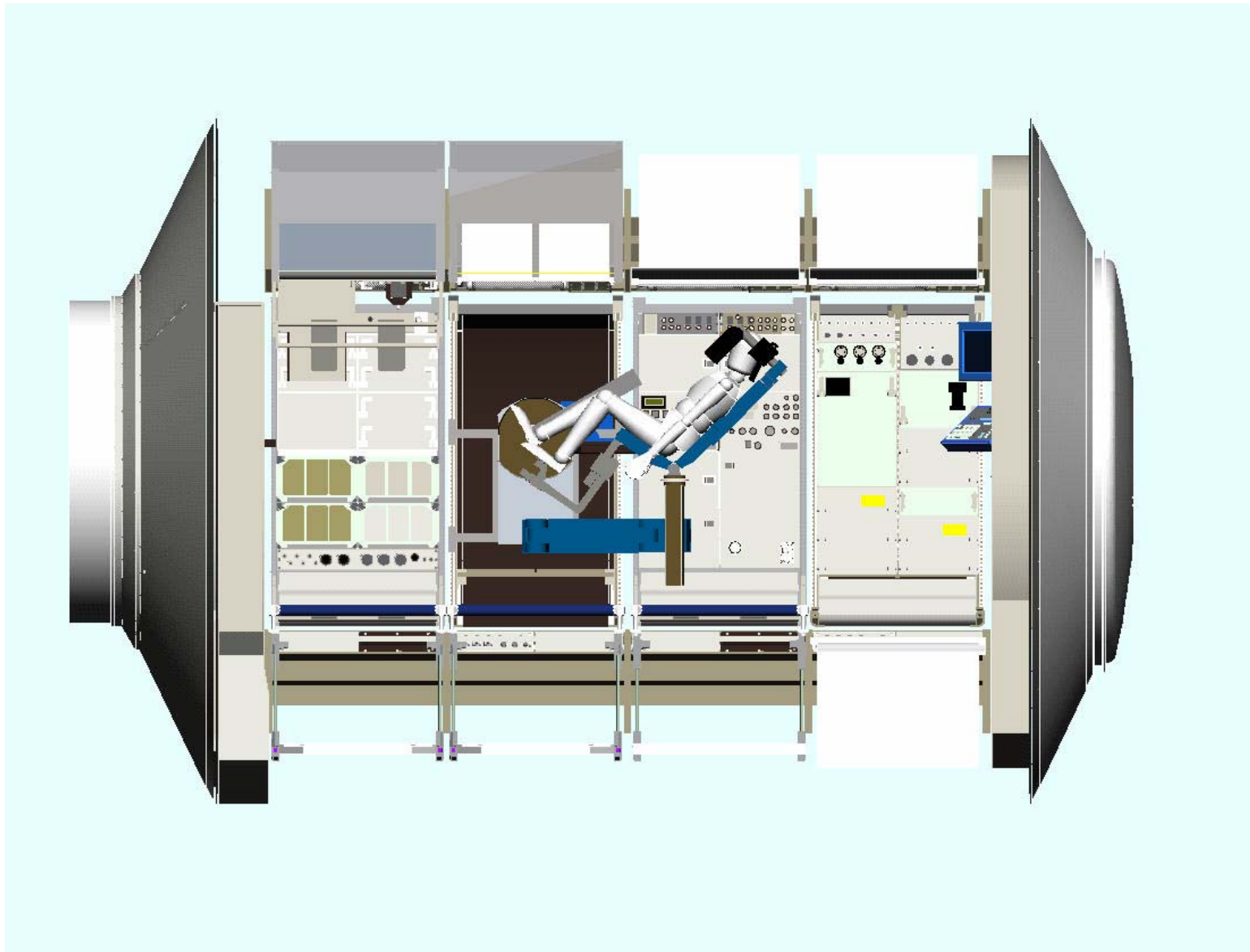
4.1 QUASI-STATIC LOAD FACTORS

The design load factors for the integrated rack and components for lift-off, landing ground handling, and on-orbit maneuvering will be applied per paragraph 3.1.1.3, SSP 57000E [Ref. 2]. Table 4-1 presents the load factors as delineated by SSP 57000E.

Table 4-1: Rack accelerations

Event	Nx (g)[*]	Ny (g)[*]	Nz (g)[*]	Rx (rad/s^2)[**]	Ry (rad/s^2)[**]	Rz (rad/s^2)[**]
Liftoff	±7.0	±8.0	±7.8	±70.8	±21.7	±34.8
Landing	±5.3	±7.2	±9.0	±37.1	±23.0	±28.3
Ground Handling	±0.5	±1.0	+2.0/-0.0	0.0	0.0	0.0
On-orbit	0.2 in any direction			N/A	N/A	N/A
* In term of acceleration. The load factors are equal in magnitude and opposite in direction from accelerations						
** Rotations taken about rack center of mass						

For early design, the load environment defined in Table 3.1.1.3-4, " Payload ISPR Mounted Equipment Load Factors (Equipment Frequency 35 Hz)", of SSP 57000E will be used for fixed interface analysis of rack-mounted components.

Table 4-2 reiterates the load factors as provided in Table 3.1.1.3-4 of SSP 57000E.

The design load factors for the rack and rack-mounted payload presented in Table 4-1, Table 4-2, and MARES-0000-PL-177-NTE will be superseded by results from coupled load analyses performed by the Space Shuttle Program. Lockheed Martin will perform a loads comparison between the design loads and the coupled loads for the MARES, the integration structures, and the ISPR to ensure design loads used for the analysis are

adequate. In the event that the coupled loads are higher than the design loads, re-analysis will be performed by the responsible organization as defined in section 3.5.

Table 4-2: HRF MARES Rack Mounted Equipment Quasi-Static Load Factors

Event	Nx (g)	Ny (g)	Nz (g)
Liftoff	±7.7	±11.6	±9.9
Landing	±5.4	±7.7	±8.8
Load factors apply concurrently in all possible combinations for each event and are shown in the rack coordinate system.			

4.2 RANDOM VIBRATION LOAD FACTORS

Random vibration loads due to ascent vibration will be combined with the quasi-static load factors for analysis of rack-mounted payload for HRF MARES Rack.

All MARES-unique hardware including MARES integration structures, which are hard-mounted to the ISPR structure for the launch phase, will be analyzed with vibration loads.

SSP 57000E[Ref. 2], Section 3.1.1.3, provides the random load environments for rack-mounted equipment weighing both less than or equal to 100 lbs and more than 100 lbs. Since the MARES with rack integration hardware weighs considerably more than 100 lbs, the random vibration environment for equipment weighing more than 100 lbs will be used for random load development for payload equipment. (A stowage drawer, weighs likely less than 100 lbs, is being added to the MARES Rack. Applicable Random load environment for the drawer is being determined and will be addressed in this document.)

Table 4-3 presents the random vibration environment applicable to MARES equipment.

Table 4-3: Random Vibration Environment for MARES Rack Equipment

Frequency (Hz)	PSD (g^2/Hz) or Slope (dB/octave)
20	0.002 g^2/Hz
20 - 70	+4.8 dB/octave
70 - 150	0.015 g^2/Hz
150 - 2000	-3.7 dB/octave
2000	0.0006 g^2/Hz
Composite	2.4 g_{rms}

The MARES Main box and peripheral equipment were previously slated to launch by means of an ISS Resupply Stowage Platform (RSP). Analysis of the MARES Main Box has therefore been conducted based on the random load environment appropriate for RSP as the launch platform. Table 4-4 presents the applicable RSP random load factors that have been used for the MARES Main Box.

Table 4-4: MARES Main Box Random load spectrum for RSP

Frequency (Hz)	PSD (g^2/Hz) or Slope (dB/octave)
20	0.001 g^2/Hz
20 - 70	+9.8 dB/octave
70 - 300	0.060 g^2/Hz
300 - 2000	-6.5 dB/octave
2000	0.001 g^2/Hz
Composite	5.3 g_{rms}

Since the load spectrum in Table 4-4 is more stringent as compared to the current random load requirement, analysis results of the Main Box based on Table 4-4 are considered valid and conservative for the launch configuration defined in this document.

The random load factors will be computed by mean of Mile's equation as outlined in Section C.3, SSP 52005B [ ]. Mass participation method for computing the random load will be used when the Mile's equation alone produces too conservatively high random loads that reciprocate negative margins, and hardware redesigns is not feasible.

The Mile's equation, as provided in Section C.3 of SSP52005B[]:

$$RVLF = 3 * \left(\left(\frac{\pi}{2} \right) * Q * f_n * PSD_n \right)^{1/2}$$

where,

Q	=	Amplification factor
f_n	=	System fundamental frequency (Hz)
PSD_n	=	Power spectral density at f_n (g^2/Hz)

Component frequencies for MARES Rack will be determined by FEM analysis. An amplification factor (Q) of 10 will be used for hard-mounted components. Q value of zero (no random load) will be applied for soft-stowed hardware.

4.3 LOAD COMBINATIONS

The random load factors will be combined with the quasi-static load factors to form the combined load factors by the root sum square method (RSS) per SSP 52005, Rev. B, (Table 4.1.2-1):

$$C_x = 1.5 \pm [N_x/|N_x|\,]\,[(N_x - 1.5)^{2} + R_x^{2}]^{0.5}$$

$$C_y = \pm\,[N_y^{2} + R_y^{2}]^{0.5}$$

$$C_z = \pm\,[N_z^{2} + R_z^{2}]^{0.5}$$

Where,

R_i = Random load factor in the i-direction

N_i = Quasi-static load factor in the i-direction

N_i = Combined load factor in the i-direction

The random loads will be combined with the quasi-static load one direction at a time in the analysis of rack-mounted hardware.

4.4 GROUND HANDLING LOADS FOR HRF MARES RACK AND PAYLOAD

The MARES rack and payload equipment will be analyzed for the Ground Handling Load Factor per Table 4-5 (Table 4.11.1, LS-71053-1[Ref. 5]). (Note from/for Doan: Official source for Table 4.11.1 is to be identified. This table is almost the same information provided in Section 2.1.11 of D683-43600).

Table 4-5: Ground Handling Loads Table

Transportation	Limit Load Factors (g)		
Environment	Longitudinal	Lateral	Vertical
Truck/Road			- 3.5
	+/- 3.5	+/- 2.0	+ 1.5
Barge Water	+/- 5.0	+/- 2.5	+/- 2.5
Dolly/Land	+/- 1.0	+/- 0.75	+/- 2.0
Air Freight	+/- 3.5	+/- 3.5	+/- 3.5

4.5 CREW INDUCED LOADS

The MARES rack and payload will be analyzed for crew-induced load per load magnitudes presented in Table 4-6 (a reproduction of table 3.1.1.3-1, SSP 57000E).

Table 4-6: Crew-Induced Loads

CREW SYSTEM OR STRUCTURE	TYPE OF LOAD	LOAD	DIRECTION OF LOAD
Levers, Handles, Operating Wheels, Controls	Push or Pull concentrated on most extreme edge	222.6 N (50 lbf), limit	Any Direction
Small Knobs	Twist (torsion)	14.9 N-m (11 ft-lbf), limit	Either direction
Exposed Utility Lines (Gas, Fluid, and Vacuum)	Push or Pull	222.6 N (50 lbf)	Any Direction
Cabinets and any normally exposed equipment	Load distributed over a 4 inch by 4 inch area	556.4 N (125 lbf), limit	Any Direction
Legend: ft = feet, m = meter, N = Newton, N-m = Newton meter, lbf = pounds force			

SSP 57000, Rev. E, Table 3.1.1.3-1

4.6 THERMAL LOADS

Impact of the thermal loading on HRF MARES Rack and payload will be determined and combined with quasi-static, vibration, and pressure loads for analysis as applicable. The thermal design environment for the ISPR are as provided in SSP41017B [Ref. 14] and SSP57000E[Ref. 2]. The thermal design environment for the rack-mounted payloads are as defined in section 3.9.4 of SSP 57000E.

4.7 PRESSURE LOADS

Impact of pressure loads on MARES Rack and payload will be determined and combined with quasi-static, vibration, and thermal loads for the analyses as applicable. The pressure design environment for HRF payload is provided in the Section 3.1.1.4 of SSP 57000E [Ref. 2]. The Pressure design environment for the rack is provided in Section 3.2.1.4.4 of SSP41017B [Ref. 14].

4.8 DEPRESSURIZATION/REPRESSURIZATION

Payload structures containing trapped volumes will be identified and analyzed for positive margins for MPLM and Space Station depressurization/repressurization. The maximum depressurization/repressurization rates that will be used for the rack and rack payload are as follows:

For space station (per Paragraph 3.1.1.4, SSP57000E [Ref. 2] and Paragraph 3.1.7.2.1, SSP41002[Ref. 14]):

> Depressurization rate: 7.64 psi/min, from 15.2 psi to 0 psi
> Repressurization rate: 2 psi/min., from 0 psi to 15.2 psi

For MPLM (per Paragraphs 3.1.1.2 and 3.9.1.1, SSP57000E [ref. 2]):

> Depressurization rate: 7.75 psi/min., from 15.2 psi to 0 psi
> Repressurization rate: 6.96 psi/min., from 0 to 15.2 psi

In addition to depressurization and repressurization, hardware equipped with a Portable Fire Extinguisher (PFE) access port will be analyzed for positive margins of safety for PFE discharge per rate given in Figure 5-1 (Figure 3.1.1.4-1, SSP57000E):
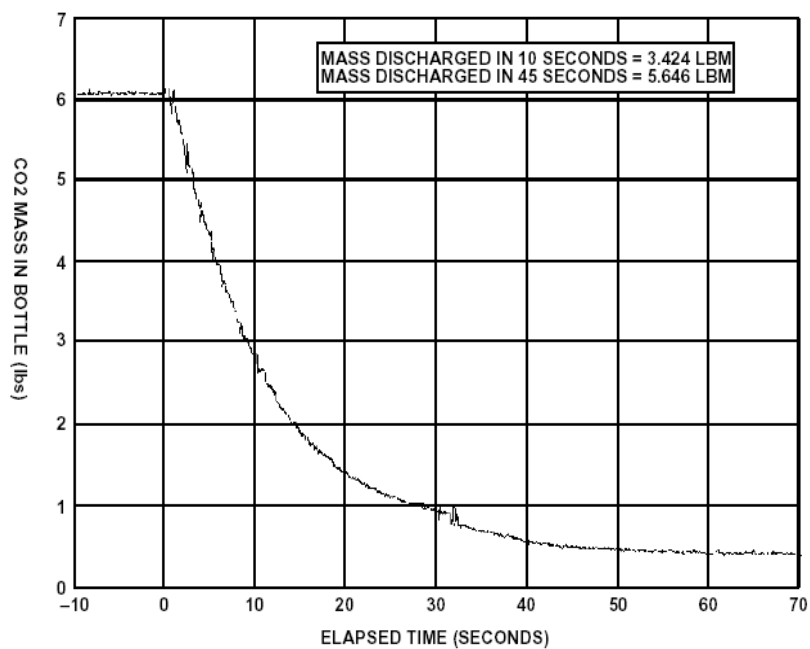
FIGURE 3.3.3.2.2–1 MANUAL FIRE SUPPRESSION SYSTEM PERFORMANCE CHARACTERISTICS AT THE RACK I/F

Figure 4-1: Manual Fire Suppression Discharge Rate(Fig. 3.3.3.2.2-1, SSP 41002)

5. MATERIALS

All materials, including non-metallic, selected for the manufacture and construction of the MARES rack and payload support structures will meet the requirements specified in applicable requirements documentation (MSFC-HDBK-527/JSC 09604, "Materials Selection List for Space Hardware Systems"; SSP 30233, "Space Station Requirements for Materials and Processes"; MSFC-SPEC-522B, "Design Criteria for Controlling Stress Corrosion Cracking"; NSTS 1700.7B, "Safety Policy and Requirements for Payloads Using the Space Transportation System"; and NSTS 1700.7 ISS Addendum, "Safety Policy and Requirements for Payloads Using the International Space Station"). JSC/EM2 will review and approve all materials used for HRF MARES Rack.. All materials including non-metallic, selected for the manufacture and construction of the MARES payload will meet the requirements documentation of ESA and will be certified by ESA materials group.

5.1 MATERIAL PROPERTIES

Material properties for metallic parts will be taken from MIL-HDBK-5H; A-basic or S-basis values will be used.

Material allowables the ISPR are to be based upon the derived/tested valued provided in SSP41017B[Ref. 14] and SSP57007[Ref. 3].

5.2 TEMPERATURE EFFECTS

Per Section 3.9.4 of SSP57000E, a maximum lift-off and landing temperature of $107.6\,^{o}$ Fahrenheit will be assumed for the MARES Rack structure and the material properties will be de-rated accordingly. Section 3.9.4, SSP57000E also indicates a maximum on-orbit temperature of $114.8\,^{o}$ Fahrenheit, and this temperature will be used as degradation temperature for kick load analysis.

6. DESIGN FACTORS OF SAFETY

Untested factors of safety will be used to calculate the margins of safety for the MARES Main Box, peripheral hardware, and rack integration hardware. The minimum factors of safety applicable to the design of the hardware are in accordance with SSP 52005, Rev. B, Table 5.1. 2-1. Table 6-1 reiterates the minimum factors of safety.

Table 6-1: Factors of Safety for MARES Main Box. Peripheral, and Integration Hardware

EVENT	FACTOR OF SAFETY	
	YIELD	ULTIMATE
Liftoff / Landing		
- Untested Structure	1.25	2.0
- Panel Buckling		2.0
- Fail-Safe		1.0
- Fasteners	1.25	2.0
- Rivets	1.25	2.0
Emergency Landing		1.0
Crew Induced Loads	1.25	2.0

Factors of safety for the soft-stowage boxes are TBD.

Both tested factors of safety (1.4 for ultimate and 1.0 for yield) and non-tested factors of safety (2.0 for ultimate and 1.25 for yield) will be used for the analysis of ISPR structure. Identification of ISPR tested structures members as well as applicable allowables are provided in SSP 41017B[Ref. 14] and SSP 57007[Ref. 3].

7. MARGINS OF SAFETY

The margins of safety for all structural components must be greater than zero for all the combined conditions. Margins of safety will be based on the strength capability of the component expressed in terms of load or stress. Buckling, crippling, tension, shear, bending, and torsion will be considered ultimate failures.

For uniaxial, simple bending, or shear loads, the ultimate margin of safety will be computed as:

$$MS_{ult} = (Breaking\ Load/\ (FS_{ult}\ x\ Limit\ Load)) - 1$$

or,

$$MS_{ult} = (Ultimate\ Stress\ Capability\ /\ (FS_{ult}\ x\ Limit\ Stress)) - 1$$

The yield margin of safety is computed similarly.

For combined loads, such as bending and shear acting on the same plane, interaction formulas will be used. Interaction formulas are dependent on the stress ratio R for each type of loading and the nature of the loading:

$$R = Limit\ Load\ (or\ Stress)\ /\ Critical\ Load\ (or\ Stress)$$

A subscript is associated with R to indicate the type of loading (i.e., R_t for tension, R_s for shear, etc.). The margin calculation is then based on a function of the stress ratios, which is dependent on the nature of the loading.

8. STRENGTH VERIFICATION

The MARES rack and payload complement will be analyzed for conformance to the strength requirements specified by SSP57000E [Ref. 2] and SSP52005B [Ref. 1].

The ISPR structure will be analyzed by Boeing in accordance to the material strengths, failure modes, and analysis requirement defined in SSP57007 [Ref. 3] and SSP41017B [Ref. 14].

The MARES Main Box, VIF, Pantograph, Chair will be analyzed by NTE/ESA and the rack integration hardware with be analyzed by LMSO for all failure modes identified in this section.   All analyses will be performed by finite element method with augmentation by hand analysis where appropriate. Finite element development will be based upon the guideline provided in Appendix D, SSP 52005B. Prior to model delivery and/or analysis, integrated rack and payload FEMs will be checked for model quality/integrity per SSP52005 and SSP57007 guidelines.

8.1 STRESS ANALYSIS

The final design structural analysis will fully substantiate the structural integrity of each piece of the MARES rack and equipment. The analysis will be based on final design, configuration, updated drawings, materials list, and environmental data. The structural model will be an extension of the preliminary design model with enough details to establish loads and load path in all critical structures.

The final stress analysis report will have the following analyses.

8.1.1   Plate and Beam Element Analysis

All plate and beam elements are analyzed based on the maximum principal and von Mises stresses recovered from NASTRAN. Von Mises stress will be used to calculate the yield margins of safety and maximum principal stress will be used to calculate the ultimate margins of safety.

8.1.2   Fastener Analysis

Fasteners will be represented as bar or rigid elements. Forces and moments are to be recovered from NASTRAN and resolved into shear and tensile forces. Preloads are to be included in the analysis of fasteners. Preload is to be calculated based on the formula given in NSTS 08307, Rev. A [Ref. 10], Section 3.3. The total tensile load is to be

calculated by summing maximum preload and axial load (including heel/toe bending) per NSTS 08307 Rev. A, Section 3.7. Total tensile load and shear load are used to calculate the margin of safety using the interaction equation given in Reference 11, Section D1.8.

Joint separation will be checked per Section 3.9 of NSTS 08307, Rev. A. A joint separation factor of safety of 1.2 will be used for joint separation check.

Torque ranges from MSFC-STD-486B, "Torque Limits for Standard Threaded Fasteners" [17] will be used for installation of fasteners and application of torque to fasteners in structural joints.

No rivets are anticipated as part of the rack or payload design for the MARES rack. In case of rivets, no heel/toe force or preload is to be applied as part of the analysis. The axial load and the shear load are used to calculate the margin of safety using the interaction equation given in Reference 11, Section D1.25.

To ensure the integrity of fasteners used for the MARES rack and equipment, lot testing will be performed to verify compliance with strength and chemical composition requirements for the fasteners per *JSC Fastener Integrity Testing Program* (JSC-23642, Revision E) or similar Program sponsored by ESA.

8.1.3   Bearing/Sheet Pull Out Check

Bearing on the panel is from the shear loads on the fasteners. Sheet pullout forces are generated by the fastener tension. Bearing allowable loads and sheet pull out allowable loads are calculated based on Section D1.10 in Reference 11. Bearing allowable loads and shear loads are used to calculate the bearing margin of safety. Sheet pull out allowable loads and axial loads (including heel/toe force) are used to calculate the sheet pull out margins of safety.

8.1.4   Shear Tear Out Check

Shear tear out is a function of panel thickness and edge distance. Shear tear out allowable loads is calculated based on Section D1.10 in Reference 11. Shear tear out allowable loads and shear load are used to calculate the shear tear out margins of safety.

8.2 BUCKLING AND CRIPPLING ANALYSIS

Maximum compressive forces are recovered from the static loads. Average compressive buckling stress is obtained from Reference 11 and the maximum critical load is

calculated based on panel dimensions. The margin of safety for buckling is calculated using maximum compressive force and maximum critical load.

The margin of safety for crippling is calculated based on the Needham Method defined in Reference 11, Section C7.2.

8.3 FAIL-SAFE ANALYSIS

For fail-safe analysis, it must be shown that the structure that remains after any single failure of a supporting member in the load path is capable of withstanding the redistributed load. A static analysis is performed with the most highly loaded fastener removed. Ultimate margins of safety are calculated, with a factor of safety of 1.0, for the remaining fasteners. Analysis will also be performed to verify that the remaining structure has sufficient fatigue life to complete the mission.

8.4 CREW-INDUCED LOADS ANALYSIS

Crew induced loads analysis is performed based on the loads in Table 7.6 and maximum stress due to the above load is calculated. The margins of safety are calculated based on material yield and ultimate strengths.

8.5 FATIGUE ANALYSIS

Analysis will be performed to ensure adequate fatigue life and to preclude failure resulting from cumulative damage due to cyclic loading and sustained stress during the design service life. The number of missions is to be calculated based on Miner's Rule documented in SSP 52005, Rev. B., Section 6.2.8 or by NASA/FLAGRO crack growth program.

9. FRACTURE CONTROL

The MARES will meet all the fracture control requirements of LS 71010A, HRF Fracture Control Plan. A fracture control summary report will be submitted for approval.

10. RAPID SAFING

MARES will meet the rapid safing requirements of letter MA2-96-190. As the crewmember is a test subject, it is required to permit egress from MARES in less than 30 seconds. This will be ensured by using fast-release mechanisms on the restraints, and verified by test.

11. MINIMUM SYSTEM-MODE FREQUENCY REQUIREMENTS

The MARES integrated rack with knee brace, mounted directly to a primary structure (USL, MPLM, e.g.), will be verified for the minimum 25 Hz requirement based on constraining at the MPLM attachment points. The verification will be performed by NASTRAN constrained normal mode analysis and confirmed by modal test at the integrated rack level. Hardware mounted directly to the rack structure will be verified for the minimum 35 Hz requirement based on constraining at the rack interface.

For the MARES Main Box and its rack integration hardware, the locations where the MARES Launch/Stowage Plate interfaces with the Launch/Stowage Plate Support Structure will be considered as the rack interface points for this rack-mounted payload assembly. The Launch/Stowage plate Support Structure is considered as a rack enhancing structure and will not be included as part of the payload analysis for 35 Hz requirement for the rack-mounted payload.

12. MODEL VERIFICATION

A NASTRAN Test-Verified Finite Element Model (TVFEM) of the integrated MARES rack model will be submitted to the cargo element integrator for Verification Coupled-Load Analysis. The MARES Rack and payload will be test- verified at two distinct levels.

The first level will be by frequency identification of the MARES main box (including the static lever) attached to the LSA. The MARES Mainbox model is prepared and verified by NTE/ESA according to the MARES Structural Verification Plan, MARES-0000-PL-177-NTE.

The second will be at the integrated rack level. The ISPR model is prepared by Boeing, and the integration structure models are prepared by Lockheed Martin. The ISPR and integration hardware are to be verified by Modal Survey by Lockheed Martin. The model verification for TVFEM for the MARES rack and payload will be performed in accordance to Section 4.0 – TVFEM Verification – of LS-71012A [Ref. 16] and Section 7.1 – Verification Requirements for Dynamic Structural Models – of SSP 52005B. Table 12-1 reiterates the applicable FEM verification requirement for the MARES Rack and payload as presented in Table 7.1-1, SSP 52005B.

Table 12-1: Finite Element Model Verification Table

EQUIPMENT ITEM	VERIFICATION
$Wt < 40$ lb (pounds) and $f_{1i} < 35$ Hz	NASTRAN model with frequency identification up to 50 Hz in all directions by resonance search
$Wt < 40$ lb and $f_{1i} > 35$ Hz	Analytical Model Only
$40 \leq Wt < 70$ lb and $f_{1i} < 35$ Hz	NASTRAN model verified by Modal Survey up to 50 Hz
$40 \leq Wt < 70$ lb and $f_{1i} \geq 35$ Hz	NASTRAN model with frequency identification up to 50 Hz in all directions by resonance search
$Wt \geq 70$ lb and $f_{1i} < 35$ Hz	NASTRAN model verified by Modal Survey up to 50 Hz
$Wt \geq 70$ lb and $f_{1i} \geq 35$ Hz and $f_{2i} < 50$ Hz	NASTRAN model verified by Modal Survey up to 50 Hz
$Wt \geq 70$ lb and $f_{1i} \geq 35$ Hz and $f_{2i} \geq 50$ Hz	NASTRAN model with frequency identification up to 50 Hz in all directions by resonance search

SSP 52005, Rev. B, Table 7.1-1

A pre-test analysis will be performed and a modal test plan will be prepared prior to the model testing and correlation for the rack.

13. ENVIRONMENTAL TESTING

Per Section 7.2.2, SPP 52005B[Ref. 1], functionality and workmanship of the MARES Rack hardware that contains electronic parts and are to be hard-mounted for lift-off will be verified through random vibration testing. MARES Rack components falling into this category includes the MARES Main Box. Details of the environment testing for the MARES are as follows:

13.1 QUALIFICATION VIBRATION TEST (QVT) AND QUALIFICATION FOR ACCEPTANCE VIBRATION TEST (QAVT)

Table 13-1 shows the QVT spectrum for the MARES per SSP 52005B requirement. Table 13-2 shows the QAVT spectrum extracted from the same document.

QVT and QAVT for the MARES will be performed by NTE/ESA. The test will be combined and performed on a qualification unit. The LSA will be attached to the MARES (in the launch configuration) and served as an interface between the MARES and test bed. Figure 13-1 shows test configuration for the MARES and LSA assembly. The test duration will be 120 second for each of the three orthogonal axes.

Table 13-1: Qualification Vibration Test (QVT) Spectrum

Frequency (Hz)	PSD (g^2/Hz) or Slope (dB/octave)
20	0.002 g^2/Hz
20 - 70	+4.8 dB/octave
70 - 150	0.015 g^2/Hz
150 - 2000	-3.7 dB/octave
2000	0.0006 g^2/Hz
Composite	2.4 g_{rms}

Table 13-2: Qualification Acceptance Vibration Test (QAVT) Spectrum

Frequency (Hz)	PSD (g^2/Hz) or Slope (dB/octave)
20	0.0170 g^2/Hz
20 - 80	+3.0 dB/octave
80 - 350	0.06076 g^2/Hz
350 - 2000	-3.0 dB/octave
2000	0.0120 g^2/Hz
Composite	7.9 g_{rms}

13.2 ACCEPTANCE VIBRATION TEST (AVT)

The flight unit of the MARES Main Box will be subjected to an AVT vibration in accordance to SSP52005B requirement. Table 13-3 shows the test spectrum for AVT for the main box. Duration for the test will be 60 second per axis.

The AVT for the MARES Main Box will also be performed by NTE/ESA.

Table 13-3: Acceptance Vibration Test (AVT) Spectrum

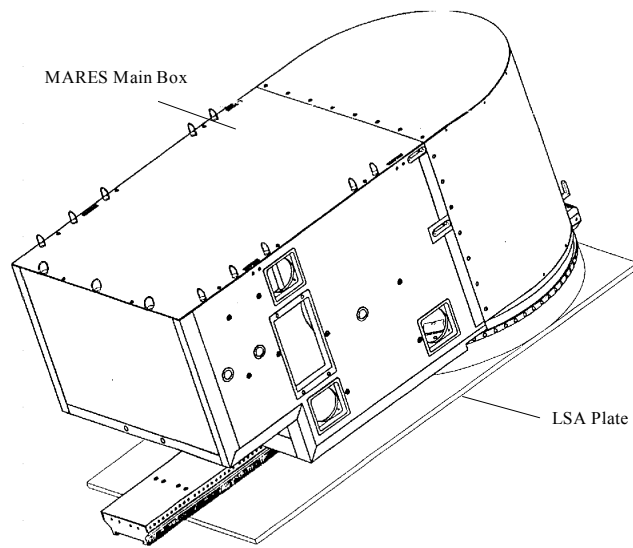| Frequency (Hz)	PSD (g^2/Hz) or Slope (dB/octave)
20	0.0100 g^2/Hz
20 - 80	+3.0 dB/octave
80 - 350	0.040 g^2 /Hz
350 - 2000	-3.0 dB/octave
2000	0.0070 g^2/Hz
Composite	6.1 g_{rms}

MARES Main Box

LSA Plate

Figure 13-1: Vibration Test Configuration for MARES Main Box

14. DOCUMENTATION

Detailed reports will be generated to document all verification analyses. Stress analysis reports will be produced to document the structural analysis, crew-induced loads analysis, depressurization/repressurization analysis, fail-safe analysis, fatigue analysis, and fracture control assessment. A finite element model report will be produced to document the model development, dynamic analysis, and correlation of the FEM. In addition, a test plan will be generated to document pre-test analysis. Test reports published by the NTE will be available to support the final hardware certification.

15. SCHEDULE

1. Structural Verification Plan…………….. .... May 2003.
2. Stress Analysis Report for MARES .... TBD.
3. Fracture Control Summary Report for MARES .... TBD.
4. Finite Element Model Report for MARES .... TBD.
5. Stress and Fracture Analysis Report for Integration Hardware .... TBD.
6. Stress and Fracture Analysis Report for ISPR .... TBD.

16. REFERENCES

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18. JSC 23642, Rev. E, JSC fastener Integrity Testing Program, date ?